Positron AMS-02 Anomaly: Single SNR Explanation without DM or Pulsar Contributions

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Outline

1 Preliminary Information
   • DSA - The Diffusive Shock Acceleration
   • DSA@SNR: Test Particle vs Nonlinear

2 Disagreements with the standard DSA
   • Anomalies in positron spectrum
   • EXISTING explanations and their weaknesses

3 NEW: Minimum assumptions, single source (SNR) scenario
   • $e^\pm$ asymmetry of acceleration: Molecular Clumps
   • Minimum in $e^+/(e^+ + e^-)$: NL DSA

4 Conclusions: no room (almost) for DM/Pulsars contribution
Essential DSA (aka Fermi-I process, E. Fermi, ~1950s)

Linear (TP) phase of acceleration

- CR trapped between converging mirrors:
  \[ p \Delta x \approx const \]
- CR spectrum depends on shock compression, \( r \):
  \[ f \sim p^{-q}, \quad q = 3r/(r - 1), \]
  \[ r = q = 4, \quad \text{Mach } M \to \infty \]

NL, with CR back-reaction

- Sub-shock
- NL-modified flow

Index \( q \) becomes \( q(p) \):
- soft at low \( p \):
  \[ q = 3r_s/(r_s - 1) \sim 5 \]
- hard at high \( p \):
  \[ q \to 3.5 \]
- for \( M > 10 \), \( E_{\text{max}} \gtrsim 1 \) TeV
  acceleration must go nonlinear
Positron Anomaly (excess)

- Positron excess (Accardo et al 2014)
- Observed by different instruments for several years
- Dramatically improved statistics by AMS-02 (published in 2014)

Things to note:
- Remarkable min at $\approx 8$ GeV
- Unprecedented accuracy in the range 1-100 GeV
- Saturation (slight decline?) trend beyond 200 GeV
- Eagerly awaiting next data release!
Suggested explanations of positron excess

- **focus on the rising branch** of $e^+/(e^+ + e^-)$
- invoke secondary $e^+$ from CR $pp$ with thermal gas

**Problems:**
- Tensions with $\bar{p}$: secondaries with differing spectra
- Poor fits, free parameters, no physics of 8 GeV upturn...

**Alternative suggestions:**
- Pulsars (lacking accurate acceleration models)
- Dark matter contribution ??

Stating the Obvious ....
- DSA@SNR’ predictive capability $\gg$ Pulsar or DM models
- $\rightarrow$ DM/P only if the DSA@SNR fails

**Upshot**
- SNR contribution **constrains** DM/Pulsar contributions
The Wishlist

- account for $e^+$ fraction by a single-source, a nearby SNR
- explain physics of decreasing and increasing branches, 8 GeV min
  - → lends credence to high energy predictions
- understand $\bar{p}$ flat spectrum as intrinsic, not coincidental:
  - most likely $\bar{p}$ accelerated similarly to protons, whenever injected
  - BUT:
    - $\bar{p}/p \neq e^+/e^-$ - Why so?
- plausible answer: acceleration/injection is charge-sign and mass/charge ratio dependent
- understand the physics of charge-sign selectivity
The Hints

- $\bar{p}$ fraction is flat on the rising $e^+$ fraction branch $E > 8$ GeV
- Opposite trends in $e^+/e^-$ and $\bar{p}/p$ spectra at $E < 8$ GeV
- Both are \textit{fractions}, thus eliminating charge-sign independent aspects of propagation and acceleration (still, HS effects?)
- Striking similarity with NL DSA solution, assuming most of $e^-$ are accelerated to $p^{-4}$ (standard DSA)
The Assumptions

- SNR shock propagates in “clumpy” molecular gas \( n_H \gtrsim 30\text{cm}^{-3} \), filling factor \( f_V \sim 0.01 \)
- High-energy protons are already accelerated to (at least) \( E \sim 10^{12}\text{eV} \) to make a strong impact on the shock structure (CR back reaction, NL shock modification)
  - Acceleration process thus transitioned into an efficient regime (in fact, required to, once \( E \gtrsim 1\text{ TeV} \), \( M \gtrsim 10 - 15 \) and the fraction of accelerated protons \( \sim 10^{-4} - 10^{-3} \))

- The SNR is not too far away, possibly magnetically connected, thus making significant contribution to the local CR spectrum
- Other SNRs of this kind may or may not contribute
Interaction of shock-acc’d CRs with gas clumps (MC)

- With some help from plasma textbooks...
- Maximum electric field due to $e - i$ collisions

$$E_{\text{max}} \sim \frac{m_e}{e} u_{sh} \nu_{ei} \frac{n_{CR}^0}{n_i}$$

- Maximum ES potential inside

$$\frac{e\Phi_{\text{max}}}{m_pc^2} \sim \frac{a}{1\text{pc}} \frac{u_{sh}}{c} \frac{n_{CR}}{1\text{cm}^{-3}} \left(\frac{1\text{eV}}{T_e}\right)^{3/2}$$

- Shock-acc’d CRs form a precursor: $\kappa$ - CR diff. coeff.,

$$L_p \sim \kappa / u_{sh}$$
**E in MC:** Injection/acceleration of $e^+$ and $\bar{p}$ into DSA

- Electric field traps $e^-$ and some $\bar{p}$ inside MC
- Ejects secondary $e^+$ → charge-sign asymmetry

- $e^+$ are re-accelerated in $E$ to $\lesssim 1$ GeV and readily injected into DSA
- At $E_e \lesssim$ few GeV, $e^+$ spectrum is dominated by the subshock compression ratio, $r_s$
  - Spectral index $q = q_s \equiv 3r_s / (r_s - 1)$ and the spectrum $f_{e^+} \propto p^{-q_s}$.
- At higher energies, particles perceive higher flow compression
  - PL-index inside the source $q \rightarrow 3.5$
Positron spectra cont’d

- $e^-$ are from the TP phase with $p^{-4}$ source spectra (and other TP-SNRs)
- $\Rightarrow e^+/ (e^- + e^+)$-spectrum = $p-$spectrum in $p^4 f(p)$ customary normalization

- ratio $e^+/ (e^- + e^+)$ is de-propagated and probes directly into the positron accelerator!
- before DM/pulsars are declared responsible for the excess above the SNR (blue curve), the following (prosaic) aspects may be considered:
  1. $e^+$ release from MC farther upstream (additional spectrum hardening)
  2. synchrotron pile-up near the cut-off energy
  3. electrostatic breakdown of MC with enhanced $e^+$ generation
If most of $\bar{p}$ and $p$ come from the same source as $e^+$ (generated in MCs ahead of SNR shock), the $\bar{p}$ and $e^+$ spectra should be the same as $p$ at $E \gtrsim 10$ GeV.

- Similarly, $\bar{p}/p$ should be flat if $\bar{p}$ are co-injected (albeit as secondaries) into any SNR-DSA process.
- Decline of $\bar{p}$ at lower energies is consistent with electrostatic retention in MC.
- Solar modulation may also contribute to $p - \bar{p}$ difference at lower energies.
- Flat $\bar{p}/p$ should continue up to $p \sim p_{\max}$ and decline at $p \gtrsim p_{\max}$ (secondaries with no acceleration).
Conclusions

- Secondary positrons produced in $pp$ collisions inside MCs ahead of SNR shocks and expelled into shock precursor make a seed population for the DSA.
- Shock-accelerated positrons develop a concave spectrum, characteristic for the NL DSA.
- Most of the negatively charged light secondaries ($e^-$), and to some extent, $\bar{p}$, along with the primary electrons, remain inside MCs and make less contributions to the overall spectrum.
- Due to the NL subshock reduction, the MC remains unshocked, so that secondary $\bar{p}$ and, in part, heavier nuclei accumulated in its interior largely evade shock acceleration.
- The AMS-02 positron excess is not fully accounted for only in the range $\sim 200 - 400\text{GeV}$, BUT:
- Physical phenomena to be included in the next-step model ($e^+/e^-$ run-away breakdown, Syn. pile-up, etc.) are likely to suffice for a conventional explanation of the residual excess.
Message to the Observers

Not every bump in the data is from DM